

James Webb Space Telescope Studies of Dark Energy

Jonathan P. Gardner (NASA GSFC), Massimo Stiavelli (STScI), John Mather (NASA GSFC) and the JWST Science Working Group¹

1. Introduction

The Hubble Space Telescope (HST) has contributed significantly to studies of dark energy. It was used to find the first evidence of deceleration at $z=1.8$ (Riess et al. 2001) through the serendipitous discovery of a type 1a supernova (SN Ia) in the Hubble Deep Field. The discovery of deceleration at $z>1$ was confirmation that the apparent acceleration at low redshift (Riess et al. 1998; Perlmutter et al. 1999) was due to dark energy rather than observational or astrophysical effects such as systematic errors, evolution in the SN Ia population or intergalactic dust. The GOODS project and associated follow-up discovered 21 SN Ia, expanding on this result (Riess et al. 2007). HST has also been used to constrain cosmological parameters and dark energy through weak lensing measurements in the COSMOS survey (Massey et al 2007; Schrabback et al 2009) and strong gravitational lensing with measured time delays (Suyu et al 2010).

Constraints on dark energy are often parameterized as the equation of state, $w = P/\rho$. For the cosmological constant model, $w = -1$ at all times; other models predict a change with time, sometimes parameterized generally as $w(a)$ or approximated as $w_0 + (1-a)w_a$, where $a = (1+z)^{-1}$ is the scale factor of the universe relative to its current scale. Dark energy can be constrained through several measurements. Standard candles, such as SN Ia, provide a direct measurement of the luminosity distance as a function of redshift, which can be converted to $H(z)$, the change in the Hubble constant with redshift. An analysis of weak lensing in a galaxy field can be used to derive the angular-diameter distance from the weak-lensing equation and to measure the power spectrum of dark-matter halos, which constrains the growth of structure in the Universe. Baryonic acoustic oscillations (BAO), imprinted on the distribution of matter at recombination, provide a standard rod for measuring the cosmological geometry. Strong gravitational lensing of a time-variable source gives the angular diameter distance through measured time delays of multiple images. Finally, the growth of structure can also be constrained by measuring the mass of the largest galaxy clusters over cosmic time.

HST has contributed to the study of dark energy through SN Ia and gravitational lensing, as discussed above. HST has also helped to characterize galaxy clusters and the HST-measured constraints on the current Hubble constant H_0 are relevant to the interpretation of dark energy measurements (Riess et al 2009a). HST has not been used to constrain BAO as the large number of galaxy redshifts required, of order 100 million, is poorly matched to HST's capabilities. As the successor to HST, the James Webb Space Telescope (JWST; Gardner et al 2006) will continue and extend HST's dark energy work in several ways.

¹ John C. Mather (chair), Mark Clampin, René Doyon, Kathryn A. Flanagan, Marijn Franx, Jonathan P. Gardner, Matthew A. Greenhouse, Heidi B. Hammel, John B. Hutchings, Peter Jakobsen, Simon J. Lilly, Jonathan I. Lunine, Mark J. McCaughrean, Matt Mountain, George H. Rieke, Marcia J. Rieke, George Sonneborn, Massimo Stiavelli, Rogier A. Windhorst and Gillian S. Wright.

There have been several studies of a dedicated dark energy space telescope, known as the NASA-DOE Joint Dark Energy Mission (JDEM) in the United States and *Euclid* in Europe. The mission concepts being studied would be able to address one or more of the methods for constraining dark energy. In this white paper, we review the contributions that HST has made to dark energy studies (sections 2, 3 and 4), summarize the status of the JDEM studies (section 5) and discuss possible dark energy studies with JWST (sections 6, 7 and 8), both on its own and in the context of supporting a JDEM mission. We conclude in section 9.

2. HST and SNIa

The discovery of the acceleration of the Universe was first made by Riess et al (1998) and Perlmutter et al (1999) using samples of distant SNIa discovered from the ground. The field of view of Hubble's instruments was too small to efficiently discover the supernovae at $z < 1$ on which these papers were based. However, Hubble was already at the time playing a role by securing accurate light curves of some of the highest redshift SNIa discovered from the ground (e.g. Garnavich et al 1998.)

In an accelerating universe, the distant SNIa appear fainter than in a decelerating universe. Alternate explanations include evolution in the population of SNIa or gray dust that would affect their luminosity without changing their colors. Both effects were ruled out by the discovery of supernova SN 1997ff at $z \sim 1.7$ (Riess et al 2001) in the Hubble Deep Field. The luminosity of this object is consistent with that of the universe in a decelerating phase, as expected at this redshift, and is incompatible with gray dust or simple luminosity evolution.

After establishing the existence of dark energy, the next step is to measure the Hubble constant as a function of redshift, $H(z)$, at several uncorrelated epochs. Measuring SNIa at $z < 1$, in the acceleration-dominated era and at $z > 1$, in the gravity-driven deceleration-dominated era, provides evidence of the transition. SNIa at $z > 1$ are faint and difficult to identify from the ground. In 2004, a large Hubble project, the Great Observatories Origins Deep Survey (GOODS,) conducted a deep-wide galaxy survey with the observations timed to optimize supernova searches. The survey identified 21 new SNIa, including 13 at $z > 1$ (Riess et al. 2007.) When combined with previous data these supernovae ruled out rapidly evolving dark energy and were compatible with a simple cosmological constant.

Detections of SNIa at $z > 1.4$ in GOODS (Dahlen et al. 2008) and in the Hubble Ultra Deep Field (UDF, Strolger & Riess 2006) are compatible with low rates of SNIa supernovae at high- z . The installation of the Wide Field Camera 3 (WFC3) on Hubble during Servicing Mission 4 improves Hubble's capabilities at $z > 1.4$ (e.g. Riess & Livio 2006). A recently-selected multi-cycle treasury program led by Sandy Faber will use 902 orbits with WFC3 to search for and characterize 15 to 20 SNIa at $1 < z < 2$.

An alternative to field searches for supernovae is to look within clusters of galaxies. This technique has been shown by Dawson et al (2009) to increase the search efficiency for finding SN at $0.95 < z < 1.5$ by a factor of 2 over field searches, increasing to a factor 3 improvement in the total yield of SN detections in dust-free red galaxies. Another innovation is to work with a near-infrared Hubble Diagram, which reduces the importance of dust corrections and can yield an independent measurement of the Hubble

diagram. Both these new techniques would benefit from the near-IR capabilities afforded by the WFC3 instrument.

3. HST and weak lensing

3a. The Cosmic Evolution Survey (COSMOS)

The Cosmic Evolution Survey (COSMOS; Scoville et al 2007) is a contiguous square field covering 1.64 square degrees. It was imaged by HST using 575 overlapping pointings of the ACS with the F814W filter. Four dithered exposures of 507s each were taken at each field position, and the final images reach a 5σ limiting magnitude of $F814W_{AB} = 26.6$ for galaxies in a 0.15 arcsec diameter aperture. The survey was used to map the cosmic shear in this field with both two- and three-dimensional analyses (Massey et al 2007.)

Traditional two-dimensional analysis of a weak lensing field measures the two-point correlation function of the projected weak lensing shear field. Three-dimensional analysis uses photometric redshifts to divide the galaxies into redshift bins and can constrain the growth of structure. Massey et al. (2007) measured $\sigma^8(\Omega_m/0.3)^{0.48} = 0.81 \pm 0.17$ using their 2-dimensional analysis and $\sigma^8(\Omega_m/0.3)^{0.44} = 0.866 \pm 0.085$ with their 3-dimensional analysis. The main constraint is on σ^8 , and their measurement is slightly inconsistent with the 3-year WMAP value of 0.74 ± 0.05 (Spergel et al 2007). The COSMOS measurements are limited by two main sources of systematic error, the difficulty in accounting for charge-transfer effects within the ACS CCD (Rhodes et al 2007) and limitations on the photometric redshift accuracy by not having deep enough near-infrared data.

By recalibrating the point-spread function (PSF) measurements using a spatially- and temporally-varying model and using the latest photometric-redshift measurements using ground-based photometry of the field, Schrabback et al (2009) recently extended the analysis of weak lensing in the COSMOS field to dark energy. Using 3-dimensional analysis, they were able for the first time to provide independent evidence for an accelerated expansion using weak lensing. However, their constraints on the equation of state of the dark energy are weak compared to other techniques due to the relatively small area surveyed by COSMOS.

3b. Comparison between space- and ground-based weak-lensing measurements.

It is possible to do weak-lensing measurements both from the ground and with HST, with different advantages. Ground-based weak-lensing surveys have the advantage of wide areas surveyed with instruments that have large fields of view. HST surveys, such as COSMOS, have higher spatial resolution and greater depth. When the instrument has a large field of view, containing many stars, the PSF can be mapped as a function of position within each exposure. Wide-area surveys contain more independent measurements of the shear, with greater statistical significance and less cosmic variance. Weak lensing studies with HST, however, have a much smaller PSF than ground-based surveys and reach deeper, detecting more lensed background galaxies at each point. Ground-based data is subject to seeing variations, while HST data is subject to PSF breathing due to thermal effects in the observatory's low-Earth orbit. Kasliwal et al (2008) compare weak lensing surveys from the ground and HST and find that the COSMOS survey detects about 71 galaxies per square arcmin, compared to 15 in ground-based

surveys. The greater depth and greater number of galaxies makes HST data better for three-dimensional tomographic analyses, while the ground-based surveys get better statistics on the two-dimensional analysis. In a related but independent test, they compared the ability of ground and space-based data to detect galaxy clusters using weak lensing. They found that ground-based surveys are more likely to find massive clusters at $z < 0.5$ (due to the larger area observed), while HST surveys have greater sensitivity to clusters of lower mass or higher redshift.

4. Additional HST contributions to dark energy studies

4a. Constraints on dark energy from galaxy clusters

Evolution of the cluster mass function traces the growth of linear density perturbations, and provides constraints on the dark energy that are complementary to those derived from the distance-redshift relation. Vikhlinin et al (2009) constrained w_0 to about 2% using Chandra observations of 37 galaxy clusters with $\langle z \rangle = 0.55$ and 49 low-redshift clusters that were detected in X-rays by ROSAT.

4b. Strong gravitational lensing

A strong gravitational lens system with measured time delays between multiple images provides a measure of the angular diameter distances to the lens, to the source and between the lens and source. The technique is most sensitive to H_0 , but also depends on other cosmological parameters. The results depend on the distribution of mass in the lens, and therefore are model dependent, although the mass distribution of the lens can be constrained by weak lensing analysis or stellar kinematics in the lens galaxy. Recently, Suyu et al (2010) measured time delays in the lens system B1608+656 and constrained H_0 to about 4%. Their constraints on the equation of state of the dark energy are comparable to current constraints from the BAO method (under the assumption of a flat geometry). Strong lensing of time-variable sources are rare, but the Large Synoptic Survey Telescope might find many examples (Marshall et al. 2010).

4c. The importance of H_0 to dark energy studies

Microwave anisotropy measurements with WMAP or Planck can constrain the dark energy equation of state parameter w , independent of SNIa or BAO, when coupled to accurate measurements of the Hubble constant H_0 . In addition to measuring $H(z)$, it is necessary to improve the accuracy of H_0 measurements.

Riess et al (2009a) used near-IR observations of Cepheids in six recent hosts of SNIa and in the maser galaxy NGC 4258 to determine H_0 to about 5% accuracy by directly calibrating the peak luminosity of the SNIa with the precise geometric distance obtained with the maser. Cepheids are better distance indicators in the near-IR than in visible light. By using the same instrument for a differential photometric measurement (NICMOS camera 2,) they reduced systematic uncertainties. Riess et al also tested the maser geometric calibration with direct distance measurements of 10 galactic Cepheids using parallaxes measured with Hubble's Fine Guidance Sensor. This yielded a factor 2.2 increase in accuracy in the measurement of H_0 and enabled a 10% measurement of w based on microwave anisotropy measurements alone.

5. Future prospects: JDEM, LSST, Euclid, etc.

In 2006 the Dark Energy Task Force (DETF; Kolb et al 2006) developed a figure of merit (FoM) for dark energy measurements, which is the inverse of the area of the error ellipse for the terms w_0 and w_a . When the DETF defined this FoM, the main community criticism was that it assumed part of the answer: it assumed that the first two terms of the Taylor series for w were enough to know. Although difficult to accomplish, it is important to determine the entire history of w and not just the current value and slope. In turn, that means that although the dark energy is not dominant in the early universe, and acceleration began only about 5 Gy ago, the farther back we can look, the better.

Since the various techniques produce high correlations (but in different directions) for w_0 and w_a , the FoM for a measurement is extremely sensitive to the context: what are the other measurements and what *a priori* information is assumed? In addition, systematic errors (recognized and potential) are likely to be dominant in the foreseeable future. Because of these two factors, the main conclusion of the DETF was that all the available measurement techniques need to be pushed forward. The DETF outlined a series of stages of measurements, ranging from Stage I (completed by 2006) to Stage IV (future space missions and large ground-based projects), with each making a significant jump in the FoM.

The JDEM Science Coordination Group (SCG; Gehrels et al. 2009) developed a Reference Mission that would make more than an order of magnitude improvement in the DETF FoM relative to Stage II. The JDEM would cover 0.4 to 2 μm with a 1.5 m telescope with imaging and slitless spectroscopy and large detector arrays (174 Mpix in total). With this equipment the JDEM would carry out three surveys: SNe, BAO, and weak lensing (WL). The resulting error ellipses from the three surveys are orthogonal, so that without all three surveys, the contribution to the FoM would be dramatically reduced. Table 4 of the SCG report is reproduced here:

Table 4 from Gehrels et al. 2009: Assumed data for JDEM Reference Observing Strategy and Mission.

Method	Survey Size	Survey Depth
BAO	20,000 deg^2	0.7<z<2.0, uniform exposure time, $nP=3$ at $z=2$ for zodiacal light 1.7x ecliptic pole.
WL	10,000 deg^2	$N_{\text{eff}}=30 \text{ arcmin}^{-2}$, $z_{\text{med}}=1.1$, photo-z RMS 0.04(1+z), 10^5 unbiased spectroscopic calibration redshifts.
SN	1500 SNe (optimistic) 750 SNe (conservative) + ground-based $z<0.2$ sample	$z<1.2$ (optimistic) $z<0.9$ (conservative)

There were three major submissions to the 2010 Decadal Survey regarding Dark Energy. Howell et al. (2009) outlined supernova science and described 6 projects: the Palomar Transient Factory, Skymapper, Pan-STARRS, the Dark Energy Survey, LSST, and JDEM. At present, progress has been limited by sample size, so that systematic differences among SNIa in different environments may still matter, and less than 2 dozen SNIa at $z>1$ were known in 2007. The report recommended continued work with HST and upcoming large telescopes: “The next generation of large telescopes, JWST, TMT, E-ELT, and GMT will allow spectroscopy of $z>3$ SNe, and extend studies to even higher redshifts. These studies may at last

elucidate the progenitors of SNe Ia, and enable studies of SN Ia evolution over vast stretches of cosmic time.”

Hirata & Eisenstein’s (2009) submission “Interpreting the Dark Energy Figure of Merit” is a useful tutorial on the merits of Figures of Merit, and the dangers of trying to use them.

Riess et al’s (2009b) “Dark Energy from a Space-Based Platform” discusses the value of space missions. In regard to SNIa, they say: “Type Ia Supernovae: Ground-based surveys in the coming decade will detect thousands of $z < 1$ Type Ia supernovae. However, a space observatory is the only feasible route to obtaining ~ 1000 high-precision light curves in the NIR and rest-frame V band for $z > 0.8$. At lower z the space-based calibration and NIR data will enable lower systematic errors than can be achieved from the ground. Improved dark-energy constraints from the SNIa Hubble diagram require substantial reduction in systematic errors of SNIa distance moduli, to 0.01 mag or less. They also benefit from an extension to $z > 0.8$ where we currently have only a relative handful of events from HST.” Note the emphasis on the systematic errors.

The Large Synoptic Survey Telescope (LSST) aims to survey the entire visible sky every few days. It would be excellent at discovering SNIa, and their summary paper asserts that LSST will make a major contribution to dark energy studies. About SNIa, they say “The two LSST samples are complementary: the main survey will obtain light curves in 6 bands and photometric redshifts of about million Type Ia supernovae per year (permitting a search for a ‘third parameter’ which, if not understood, might introduce systematic error in luminosity evolution; Wood-Vasey et al 2007), and the rapid sampling ‘mini-survey’ of selected areas will yield well sampled light curves of tens of thousands of supernovae to a limiting redshift beyond one (leading to an independent test of dark energy dynamics; Riess et al 2007).” Working in conjunction with a space mission that could follow up their SNIa to gain better photometry could be helpful.

The *Euclid* project of the ESA is similar in concept to the JDEM. Their summary report of December 2009 (Cimatti et al. 2009) outlines two main cosmological probes: weak lensing and BAO. It will conduct a wide-area photometric survey of 20,000 square degrees reaching galaxies out to $z \sim 2$, with slitless spectroscopy to obtain redshifts. They are studying the possibility of a micro-mirror based multi-object slit spectrograph. There will also be a deeper survey of 40 square degrees. The telescope is 1.2m and there are a total of 680 mega-pixels of detectors.

6. JWST and SNe

6a. JWST observing efficiency for wide-area surveys

Studying dark energy requires wide-area surveys, either to find and identify SNIa as they explode, or to obtain the large statistical datasets needed for weak lensing, baryon oscillation or cluster studies. JWST was originally conceived and designed to conduct deep surveys efficiently; it is similar to HST in its ability to conduct wide-area surveys, with a much lower survey mapping efficiency than missions like Spitzer, GALEX and WISE, which were optimized for efficient sky mapping.

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The efficiency of HST for wide-area surveys is limited by two things: the quantization of observing times in low-Earth orbit, and the fact that the highly accurate milli-arcsec pointing requirements means that it takes significant time to acquire guide stars. Spitzer is much more efficient, as it is in a deep-space orbit, and the pointing requirements, of order 0.1 arcsec, allow rapid settling and guide-star acquisition. JWST has the advantage of a deep-space orbit, but its pointing requirements are comparable to Hubble's.

The largest survey conducted by Hubble is COSMOS, covering 1.64 square degrees in 640 orbits. The largest Spitzer survey is SWIRE, which totaled nearly 50 square degrees in 6 fields in 840 hours. COSMOS used a single filter, while SWIRE imaged in 7 bands.

Despite its deep-space orbit, JWST's survey efficiency for wide-area surveys will be closer to that of Hubble than that of Spitzer. The JWST slewing requirement for small offsets, i.e., dithers up to 20 arcsec, is 60s of time. This assumes that a new guide star acquisition will not be necessary, a condition that will usually be met for dithers. For mosaics, or offsets up to a full field of view of the NIRCам, the requirement is 480s of time for an offset up to 280 arcsec. Finally, slews up to 90 degrees can take up to 1 hour of time.

The actual slew times are likely to be less than the requirement, although it is not a linear function of distance. Small offsets require acceleration, deceleration, settling time and guide star acquisition (if needed.) Assuming all 6 gyros are working, the expected actual slew times, not including guide star acquisition are approximately 2 arcsec in 25 sec, 10 arcsec in 45s, 20 arcsec in 55s, 300 arcsec in 150s and 1000 arcsec in 200s. A guide star acquisition will take 90s of time.

Complete imaging coverage in a wide-area NIRCам survey will require 3 dithers at each point, to fill in for bad pixels and to fill in the gaps between the chips. Experience with Spitzer indicates that 4 dithers produce a more robust dataset than 3. Lifetime and thermal considerations are likely to restrict frequent filter changes. Therefore, while a filter change might be shorter than a slew, we will probably nonetheless conduct surveys by dithering a long exposure or mosaicking a large area in each filter, rather than cycling through multiple filters at each dither or mosaic position.

The overheads in a wide-area survey, designed with 3 dithers per point followed by an offset of 1 NIRCам FOV would be: 30s for two dithers plus 150s for a FOV offset and one new guide star acquisition for 90s. The overheads total 300s per field of view per filter. The total overhead to image one square degree (360 NIRCам FOVs) in 5 filters would be about 150 hours. In this same time the field could also be imaged in 3 long-wavelength filters for "free" due to the dichroic. Each visit would need about 30 minutes as an average slew time between targets and there would be a tax between 10% and 20% to account for WFS/C and calibration operations. A minimal on-sky exposure time of 60s per readout gives a total on-sky exposure time of 90 hours per square degree, taking about 300 hours of wall-clock time. This is based on the current best guesses for the slew-and-settle times, which equal half the requirements. If instead we use the requirements, then the overheads would be twice as high, and the one square degree survey would take about 450 hours.

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If a wide-area survey was done in only two filters (one on either side of the dichroic), the overheads would be 30 hours per square degree. With 60s on-sky readout times and other overheads, the total would be about 60 hours per square degree.

For deep surveys, JWST is much more efficient, since the times to dither are much smaller than the times to offset a full field of view. We expect to read out the detector at least every 1000s; long exposures are limited by the cosmic-ray rate. If a deep survey uses 1000-second exposures and spends 30s dithering each time, the minimum overhead will be 3%, and the efficiency of the observations will be dominated by the tax for observatory maintenance rather than the offset time. Medium-deep or deep-wide surveys will have efficiencies somewhere in between.

NIRSpec multi-object observations require 900s set-up time to acquire the field and position the objects within the shutters, in addition to the telescope pointing and other overheads. For $R \sim 1000$ and $R \sim 3000$ observations there are three grating settings needed to get full wavelength coverage; for the $R \sim 100$ prism a single setting is sufficient. If we wish to set a minimum reasonable observing efficiency at about 50%, this sets a minimum NIRSpec on-source observing time of 1800s, for a total observing rate of 1 field with 100 objects at $R \sim 100$ per hour of wall-clock time. The observations would reach a continuum depth of 10σ at $AB=25.1$ at 3 microns.

6b. JWST Supernova search.

A supernova search similar to that done with Hubble on GOODS would be feasible with JWST. Hubble imaged the 320 square arcmin in two GOODS fields 19 times (1 reference epoch and 18 search epochs.) The SN rate of discovery was about 1 supernova at $z>1$ per epoch imaged, equivalent to 10 SNe per square degree per epoch. The GOODS searches used 1600s of exposure per field per epoch in F850LP and 400s in F775W. With the ACS instrument these exposure times yield 10σ at a magnitude of $AB=24.5$ in F850LP and $AB=25.1$ in F775W. A similar depth would be reached in about 30s of exposure with JWST NIRCам using F070W and F090W, however, it is likely that a JWST survey would be designed along the lines of the wide-area survey discussed in section 6a. The search epochs would need to be separated by about 6 weeks.

The supernova follow-up would include measuring the light curve and obtaining a spectroscopic confirmation for the redshift. JDEM has a large enough field of view that any given exposure is likely to have a SNIa, so it is efficient to use the same data stream to identify the SNIa and obtain light curves on a 5-day cadence. With the smaller field of view for NIRCам, most fields would not contain any SNIa, so the most efficient strategy with JWST would be to separate the search and the follow-up into separate observations. JWST would also clearly be able to follow-up supernovae found by other surveys.

The follow-up observations are also dominated by the overheads. The GOODS strategy was to obtain spectroscopic confirmation (and measure the redshift, if necessary) of the SNe, followed by 6 to 8 epochs to obtain a light curve. Although the magnitudes are bright and the exposure times short, each epoch would be a separate visit, needing 30 minutes to slew to the field (assumed average; the requirement is 60 minutes.) Here we will assume 8 light curve observations, taking a total of 1 hour

each, per supernova. There may be an additional Target of Opportunity “tax”, but we will not include that here.

We design a JWST SNe search as follows. The field would need an initial survey of 300 hours to obtain multi-filter data on 1 square degree. Successively each epoch 6 weeks later would need 60 hours and would find 12 SNIa at $z > 1$. The 12 SNIa would require an additional 96 hours for follow-up spectroscopy and light curve observations. With 5 epoch observations, a sample of 60 SNIa could be obtained within a year, using a total of 1080 hours.

Riess & Livio (2006) have argued that there would be a particular merit in observing supernovae at $z > 1.5$ in order to measure or place upper limits to supernova evolutionary or inter-galactic medium effects that might represent the limiting factor in future supernova searches. By observing SNIa in the redshift range 1.5-3 one can focus on evolutionary effects since at these redshifts the dark-energy dependent effects are negligible. The SNIa rates at these redshifts are unknown and one needs to consider a range of models assuming different values for the Type Ia delay. Longer delays mean that SNIa might be rarer at the higher redshifts, and more area or more epochs would be needed to find the same number of SNIa. At higher redshift, the optimal search strategy and delay between the search epochs is stretched by the $(1+z)$ time dilation factor.

In addition to going to higher redshift, JWST observations will allow the measurement of rest-frame near-infrared light curves (Wood-Vasey et al 2008; Freedman et al 2009.) The effects of extinction by dust are lower in the infrared, and the peak magnitudes are standard candles at the 15% level, even without correcting for light-curve shape.

Given the importance of systematics, reaching to higher redshift and observing the rest-frame near-infrared are likely to be the major contributions of JWST to the characterization of SNIa as distance indicators. However, the absolute photometry necessary will be an important constraint on JWST’s contribution to SNe cosmology. The intrinsic dispersion in optical measurements of SNIa as standard candles is about 15%. (It is not yet clear what the limits will be for rest-frame near-infrared measurements.) As the sample size exceeds 100, the statistical errors go down to $15\% / (\sqrt{100}) = 1.5\%$, reaching the current limits of systematic errors in the photometry. In particular, there exist no absolute photometric measurements of standard stars joining the optical to the near-infrared at this level. NASA is planning the sub-orbital ACCESS mission to set up these standard stars (Kaiser et al 2009). The JWST photometric requirement is 5% absolute accuracy, similar to the pre-launch requirement on Hubble. Although Hubble has exceeded this requirement, it is clear that we cannot assume that JWST will be capable of the 1% or 2% absolute photometry that is needed to take advantage of hundreds of SNe, even if JWST could find and measure them.

6c. Could JWST do the JDEM supernova spectroscopy?

As listed above, JDEM will find between 750 and 1500 SNIa, obtain spectroscopic redshifts and follow their light curves. SNIa at $z \sim 1.5$ are bright enough for JWST to obtain a spectroscopic redshift in a relatively short amount of time. If we wished for JWST to be the JDEM supernova spectrograph, it would need to be available throughout the JDEM SNIa observations to take spectra as targets of opportunity.

The overheads associated with slewing to the source, acquiring the SNIa in the NIRSpec IFU and taking data are much longer than the actual exposure time, but would probably fit within an hour per source. The observations would probably not need to be full targets of opportunity, as they can be pre-planned and pre-scheduled, with the fine pointing uploaded several days before the observation. However, the pre-scheduling of hundreds of targets might have an adverse affect on the efficiency of the observatory, and possibly even on aspects like momentum management. An allocation of 750 to 1500 hours is a substantial program, but not unreasonable. However, the detailed impact of such a program on the scheduling algorithm could end up ruling out this as a possibility. The use of JWST to obtain spectra of a sub-set of the JDEM SNe, such as those at the high redshift end, is a strong possibility.

7. JWST and weak lensing

7a. Designing a JWST weak lensing survey.

From the calculations listed in section 6a, it is clear that JWST is not able to conduct the 10,000+ square-degree weak lensing survey envisioned for JDEM, LSST or other 4th generation dark energy experiments. Even if JWST did the survey in just two filters, it would only be able to image 17 square degrees in a 1000-hour program, orders of magnitude smaller than the 10,000 square degrees envisioned in the JDEM weak lensing concepts. It is also not clear that the next generation weak lensing survey from space could get by with just two filters: cosmic shear tomography requires very accurate photometric redshifts, and the infrared depth advantage of space-based observations is lost if one were to rely on ground-based data for the photometric redshifts. A survey of 10,000 square degrees in the 8 NIRCams filters with 3 dithers on each field of view would take 340 years; clearly JWST is not going to do this part of the JDEM science objectives.

From here onward, we will consider a COSMOS-like survey done in the 8 NIRCams filters, with on-sky exposure times of 180s per point per filter, divided into three dither positions at each point. We will assume that 1000 hours was allocated to this survey, and it has covered 3 square degrees. The area is 50% larger than the COSMOS survey, and it has the advantage of multi-color data. Consistent with section 6a; JWST is therefore somewhat more efficient at wide-area surveys than HST, but much less efficient than Spitzer. The depth reached is:

Channel	Filter	Exposure time	10-sigma depth (nJy)	AB
SW	F070W	180 s	155.7	25.9
SW	F090W	180 s	106.5	26.3
SW	F115W	180 s	87.9	26.5
SW	F150W	180 s	83.4	26.6
SW	F200W	180 s	77.5	26.7
LW	F277W	180 s	92.6	26.5
LW	F356W	360 s	72.7	26.7
LW	F444W	360 s	129.1	26.1

The depth at the shortest wavelengths is comparable to that of the COSMOS survey, which reaches AB=25.9 (10σ) in the ACS F814W filter. The S-COSMOS survey, which consists of Spitzer observations of the same area, observed each point in the field for 1200s in each of the IRAC filters, and reached 10σ depths of 18 and 34 micro-Jy (AB = 20.8 and AB = 20.1) at 3.6 and 4.5 microns, respectively. Although

comparable in depth in optical wavelengths, the JWST survey will be much deeper in the near-infrared, and will reach considerably higher redshifts than COSMOS, which reaches to $z \sim 2$ with a significant tail out to $z \sim 3$. By analogy to the Riess & Livio (2006) arguments for SNIa cosmology, cosmic shear tomography at redshifts where the effects of dark energy is weak in comparison to the effects of dark matter could reveal unknown systematics in measurements made at lower redshift.

Weak lensing tomography uses photometric redshifts that are calibrated with spectroscopic redshifts. Using NIRSpec and its micro-shutter array, JWST can get 10σ $R \sim 100$ spectroscopy of 100 objects down to a continuum detection level of $F277W_{AB} = 26.5$ with exposure times of 21,000s (just under 6 hours). To calibrate the photometric redshifts with a spectroscopic redshift sample of 3000 galaxies would take a survey of 250 hours, assuming the nominal 70% JWST observing efficiency. (It should be noted that the JWST Level 1 requirement to observe 2500 galaxies would require longer exposures and would not be met with this program.)

One of the limitations on interpretations of weak lensing in HST data is the breathing of the PSF as the telescope goes in and out of sunlight in its orbit (Rhodes et al 2007; Massey et al 2007). While JWST will not be subject to breathing, the mirror is not rigid and the PSF will drift over time. The wavefront error of the mirror will be measured and corrected approximately every two weeks. Since the PSF will drift, it is possible that this will interfere with cosmic shear measurements with JWST. However, since the PSF will be very well measured within one or two weeks of every observation, it is possible that cosmic shear measurements with JWST will be less subject to systematics due to the PSF than for Hubble.

7b. Could JWST do the spectroscopic redshifts to calibrate a ground- or space-based photometric weak lensing survey?

The JDEM SCG report proposes a spectroscopic redshift survey, used to calibrate the photometric redshifts, covering an area totaling 1 square degree and obtaining data on 30,000 to 100,000 galaxies. As calculated in section 6a, JWST could obtain spectroscopic ($R \sim 100$) redshifts on 100 galaxies per hour at $AB \sim 25$. To meet the minimum requirements for the Photometric Redshift Calibration Survey for JDEM would take 300 hours of JWST time (plus 300 hours of NIRCам imaging for object selection, if that doesn't already exist.) Spectra of 100,000 galaxies would take 1000 hours of JWST time.

7c. PSF requirements for a weak lensing survey

The JWST spatial resolution will be approximately 0.06 arcsec at 2 microns, considerably better than the 0.2 arcsec expected for JDEM or Euclid. JDEM measurements of the intrinsic shapes for weak lensing, after taking out the PSF, have a required accuracy of 0.1%. This is essentially a deconvolution, and is non-trivial; deconvolution has never been done to this level. If JDEM does a wide-area weak lensing survey, having a sub-set of the area observed at higher resolution with JWST will enable an important check on the weak lensing shape analysis. This could probably be a study done with data in the JWST archive, or with a JWST wide or deep-wide survey taken for other reasons.

The PSF requirements for a JDEM weak-lensing survey are very stringent. It is expected that JDEM will need to continuously telemeter the fine guidance error signal stream, to be used to de-blur the images in ground processing. JWST does not have this capability. JWST has Level-2 requirements on the stability

of the encircled energy in the PSF, and on the stability of the pointing system. However, it does not have a requirement on the stability of the shape of the PSF itself. Although the other requirements are likely to constrain the shape of the PSF, it will not be to the extent that is needed for JDEM's mission, which would be designed and built specifically for weak lensing. Additional issues of the JWST PSF include the diffraction pattern of the hexagonal mirrors, stray light, and the repeatability of the wavefront sensing and control operations.

7d. Baryon Acoustic Oscillations

The JDEM SCG report proposes a spectroscopic redshift survey of 1.4×10^8 galaxies to derive BAO constraints on dark energy. At 100 galaxies per hour, it would take 160 years of JWST time to take spectroscopy of that many galaxies, but the galaxies would not be evenly spread over 20,000 square degrees. A more realistic requirement would be 700 years to image the area and a comparable or larger time for the spectroscopy. Regardless of the details, it is clear that a BAO survey of this type is not feasible with JWST.

8. JWST contributions to other techniques

8a. JWST measurements of galaxy clusters

Massive galaxy clusters have been identified out to $z = 1.41$ (Stanford et al. 2005). The cluster mass can be estimated either from the X-ray temperature or the velocity dispersion of the galaxies. With NIRSpec, JWST could measure the velocity dispersions of any known massive cluster, constraining the growth of structure in the universe. It would be more difficult for JWST to find and identify the massive clusters themselves, as that project requires hundreds of square degrees to find the rare peaks. For example, Coma-sized clusters at $z \sim 1$ are expected to occur at the rate of approximately 1 cluster per 100 square degrees (Subha Majumdar, private communication.)

8b. JWST follow-up of LISA sources

The Laser Interferometer Space Antenna (LISA) mission will detect and identify merging super-massive black holes throughout the observable universe. The gravitational radiation gives the exact time of the merger event, the luminosity distance to the source and positional information accurate to about 10-arcminute-sized error boxes for typical sources, and as good as 1-arcminute for optimal sources at $z \sim 1$. It is not currently known if there will be an observable electro-magnetic component to the merger event; this is a very active area of ongoing study. However, if the merging galaxies hosting the black hole merger event can be identified, perhaps through a JWST redshift survey of the area, or through JWST imaging monitoring of the positional error box during the merging event, then the independently measured redshift and luminosity distance can be used to constrain dark energy.

8c. JWST contributions to measurements of H_0

JWST will be able to contribute to further improved measurements of the Hubble constant. Its sensitivity in the near-IR will enable us to measure light curves for Cepheids to distances > 50 Mpc, expanding the set of supernova calibrators and the set of masers available to study from the single maser in NGC 4258 to more than ten. The differential nature of the measurements is independent of the absolute photometric accuracy of JWST and should be easily achievable. A given error on the Hubble constant leads to twice that error on the measurement of w . JWST might be able to achieve a 1% measurement of the Hubble constant, which would imply a 2% measurement of w .

9. Summary and conclusion

JWST is optimized for long exposures and deep observations. Dark energy studies rely on either rare events (SNIa) or very large statistical datasets (weak lensing and BAO). Unlike the concepts for a mission designed to study dark energy, JWST is not well optimized for dark energy studies.

Hubble provided the first confirmation of the existence of dark energy, and has characterized dark energy using both SNIa and gravitational lensing. In the terms of the dark energy task force, HST has served as both a Stage 1 and Stage 2 effort. The recent selection of the cosmological survey multi-cycle treasury program might begin to reach Stage 3. As the successor to Hubble, JWST will extend the SNIa studies to higher redshift and into the rest-frame near-infrared. The capabilities of JWST for weak lensing are similar to, or perhaps a factor of a few better than HST.

Summary table: JWST observations constraining dark energy.

Technique	Description	Survey	What	Hours	Comments
SNIa	GOODS-like	1 sq. deg., 5 epochs	60 SNIa	1080	Higher z , NIR rest-frame, constrain evolution, dust
SNIa, follow-up	Spectroscopy for JDEM	Redshifts	750 to 1500 SNIa	750 to 1500	Timing might interfere with JWST operations
Weak lensing	COSMOS-like	3 sq. deg., 8 filters	3-d tomography	1000	Higher z , multi-color data
WL follow-up	Photo- z calibration	Imaging, NIRSpec MOS spectra	100,000 galaxies	1300 hours	Spectroscopic calibration of photo- z JDEM survey
BAO					Not feasible with JWST
H_0	Cepheids	10 masers, SNIa hosts to 50 Mpc	Calibrate other DE studies		
Galaxy Clusters		Known massive clusters at $z>1$	Dozens		Velocity dispersions to measure mass
LISA sources	Binary black hole mergers	LISA detections	Identify electro-magnetic transient		

In support of a JDEM or *Euclid* mission weak-lensing survey, and with a major program, JWST would be able to do the spectroscopic redshift sub-sample to calibrate the photometric redshifts. It is possible that JWST could also do the spectroscopic redshifts for a JDEM SNIa search, although the logistics would be more complicated. JWST cannot do the JDEM weak lensing imaging, nor the JDEM BAO spectroscopy itself.

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